Constellation-X White Paper on Stellar Endpoints
January 2005

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Introduction

Sensitive spectroscopic observations of the X-ray emission from Compact Stellar Objects (neutron stars, white dwarfs, and black holes) can provide the most direct experimental constraints on an array of important topics in astrophysics. High resolution spectroscopy provides, among other things, a probe into stellar structure and evolution, stellar nucleosynthesis, the chemical evolution of our Galaxy, the physics of the densest states of matter, energy conversion in accretion flows, and the structure of spacetime in the vicinity of Black Holes.

The study of X-ray emitting compact stellar remnants has evolved dramatically over the last few years, since the launch of *Chandra* and *XMM-Newton*, and the most dramatic increase in our knowledge has come from spectroscopic observations with these observatories, in addition to the detection of coherent millisecond variability in X-ray bursts with the *Rossi* X-ray Timing Explorer. *To continue this development, the most important performance parameters for the instrumentation on Constellation-X will therefore be those associated with spectral resolution, effective area for high resolution spectroscopy, and the ability to observe bright sources at full sensitivity. Angular resolution, bandpass, and field of view are less critical. Some of the most important investigations will require the ability to study spectroscopic variability at the millisecond level.*

Below, we illustrate these requirements with a discussion of a series of important critical advances that the unique capabilities of *Constellation-X* will enable.

Using Neutron Stars as Probes of Fundamental Physics.

Accreting neutron stars in X-ray binary systems. These neutron stars provide the opportunity to explore important aspects of fundamental physics under extreme conditions which are not achieved anywhere else in the observable universe. The state and properties of matter at these extreme densities are in the deep interior of neutron stars, allowing us to probe the highest densities known in the universe, and testing aspects of Einstein's theory of General Relativity when the gravitational field is very strong.

The mass, M, and radius, R, of a neutron star depend directly on the physics of the interactions between fundamental particles; protons, neutrons, and at the incredible densities inside neutron stars, on the fundamental quarks from which all normal matter is comprised. The theory of such interactions, Quantum Chromodynamics (QCD for short), is both extremely complex and not sufficiently constrained to allow us to calculate the exact state of matter at such extreme densities. Perhaps the only way to constrain the theory is to make precise measurements of both the masses and radii of neutron stars. Some neutron star masses are known very accurately (Thorsett & Chakrabarty 1999, Orosz & Kuulkers 1999, Nice, Splaver & Stairs 2004). These have generally been obtained from careful observations of young neutron star pulsars in binary systems.

By observing spectral lines produced from elements (like Fe) in the atmospheres of accreting neutron stars, *Constellation-X* should be able to determine both the masses and radii of such neutron stars. The fact that these neutron stars are accreting matter from their binary companions is important for several reasons. 1) A continuous supply of metals should allow higher atmospheric abundances of the line producing elements to be present than in isolated (non-accreting) neutron stars, which should yield more prominent absorption lines. 2) Accretion of light elements also leads to thermonuclear X-ray bursts; brief but bright flashes of thermal X-ray radiation shining through the neutron star atmosphere, during which lines can be expected to form. 3) These older neutron stars may have accreted enough additional mass so that they probe the neutron star mass - radius relation in a different regime than the younger neutron star pulsars. This may allow actual mass versus radius curves for neutron stars to be obtained, which would tell us a great deal about the state of matter at extreme densities (Lattimer & Prakash 2001).

Careful study of the absorption spectrum leads in principle to a simple, direct measurement of the gravitational redshift at the surface of the star, which provides a measure of the mass-to-radius ratio, but not a separate measure of the mass *and* the radius. To do that requires additional information. Many of these accreting neutron stars are known to be spinning quite rapidly. Rotation of the neutron star produces a Doppler shift which broadens the spectral lines. By accurately measuring both the gravitational redshift and the line profile (how broad the lines are), it is possible to determine both the mass and radius of the star.

Indeed, observations of the neutron star binary EXO 0748-676 made with *XMM-Newton* have recently led to the first evidence for the presence of absorption lines during X-ray bursts (Cottam, Paerels & Mendez 2002). With its much larger collecting area *Constellation-X* will be able to make much more sensitive searches for such lines, and will be able to better measure the energies and profiles of any lines which are seen (see Figure 1). For the first time this technique has recently been applied to EXO 0748-676 (Villarreal & Strohmayer 2004). A spin frequency of 45 Hz was found for the neutron star in EXO 0748-676 using data from NASA's *Rossi* X-ray Timing Explorer (RXTE). Modeling of the observed widths of the *XMM-Newton* absorption lines using this spin frequency shows they are consistent with a neutron star radius in the range from 9.5 to 15 km. *Constellation-X* should be able to measure the radius to within a few percent by measuring the widths of the absorption lines with much greater precision than is possible with current data.

The shapes of surface absorption (or emission) lines from neutron stars can also tell us about fundamental aspects of Einstein's theory of General Relativity. Because the profiles of lines observed at infinity depend on the detailed trajectory that photons originating from different parts of the neutron star follow through the potential well, the profile shapes are sensitive to the precise magnitude of relativistic effects that affect those trajectories (Ozel & Psaltis 2003, Bhattacharyya, Miller & Lamb 2004). The most famous of those effects is the one associated with the relativistic 'dragging' of reference frames. By observing line features with the large collecting area and high spectral resolution of *Constellation-X* it may be possible to measure the amount of frame dragging, for given spin and mass of the neutron star, and thus test General Relativity.

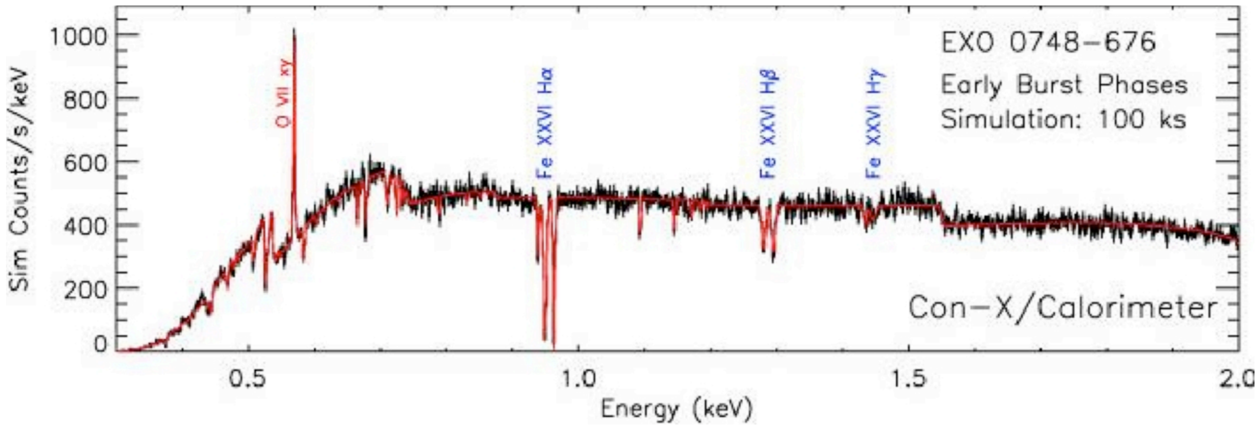


Figure 1: Simulated spectrum of the early phases of the x-ray bursts from the accreting neutron star EXO 0748-676 using the *Constellation-X* calorimeter. A 100 ks observation should result in 1 ks of burst time. The blue labeled lines are gravitationally red-shifted absorption lines from the neutron star atmosphere. The remaining spectral structure originates in the circumstellar material. The model was developed using the XMM-Newton data and theoretical calculations for the absorption line structure.

Accretion and Massive Stellar Wind Dynamics in High Mass X-ray Binaries

High-mass X-ray binaries (HMXBs) are composed of an early-type star and a compact object, either a neutron star or black hole. The companion star of a standard HMXB is an OB giant or supergiant, while a second, and more prevalent class, the Be-XRBs, harbors a rapidly spinning B-emission star. Two HMXBs have been identified as black hole systems: Cyg X-1 and LMC X-3. As bright X-ray sources, HMXBs represent a unique phase of the overall binary evolution. In the evolutionary context, mass transfer plays the dominant role (Verbunt & van den Heuvel 1995).

In studying HMXBs, one pursues an understanding of (1) the accretion of material onto compact objects – the conversion of gravitational potential energy into radiation – and (2) mass loss from early-type stars – the physics of the stellar wind that provides the accreting material (Liedahl et al. 2001). Both aspects of HMXB physics fall within the purview of X-ray spectroscopy. Recent *Chandra* observations have shown that high-resolution X-ray line spectra convey the spectral imprints of large-scale velocity fields. These spectra have provided detailed constraints on ionization distributions (and thus density fields) and by recording orbital-phase-resolved spectra, have clearly implied deviations from spherical outflow and deviations from smoothness (Paerels et al. 2000; Sako et al. 1999).

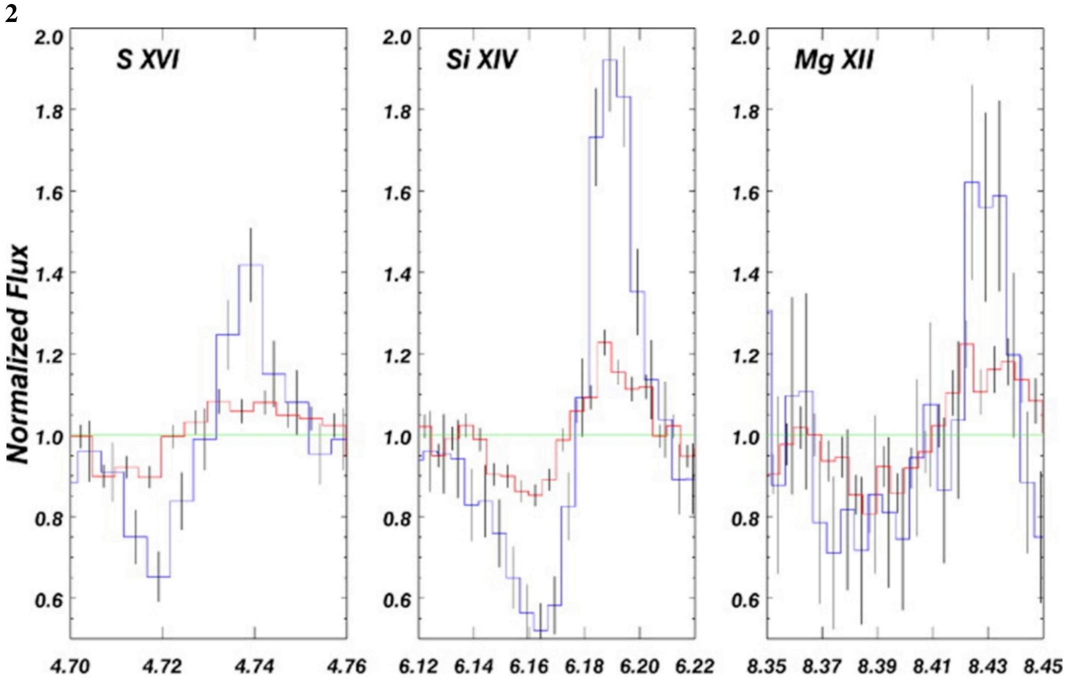
While excellent targets for detailed spectroscopic studies do exist (e.g., Schulz et al. 2002), the sample size of objects is quite limited; there are only six sources – Vela X-1, Cyg X-3, GX 301-

2, Cen X-3, Cyg X-1, 4U1700-37 – that are sufficiently bright to obtain good quality high-resolution spectra. With *Constellation-X*, we can expect to increase the sample size by roughly an order of magnitude. With larger collecting area, orbital-phase-resolved spectra can be obtained with much better time resolution. Moreover, for X-ray pulsar studies, the response of the accretion flow to X-ray pulses can be studied on much finer time scales. Intrinsic spectral variability resulting from inhomogeneities in the stellar wind becomes more readily accessible.

A central theme in X-ray spectroscopic studies of HMXBs is the assessment of the effects of the primary X-ray continuum on the physical state and dynamics of the wind (Stevens & Kallman 1990). In HMXBs we have access to ionization parameters ranging across four to five orders of magnitude, and temperatures and densities ranging across three orders of magnitude. The emission-line and absorption-line spectra are extremely rich. *Note that the two line transfer processes in HMXB winds – resonant line scattering and resonant Auger destruction – both of which profoundly constrain the structure and dynamics of HMXB accretion flows, require resolving powers of several hundred.*

Resonant line scattering competes with recombination in producing X-ray lines (Wojdowski et al. 2003). The contribution from resonance line scattering of the X-ray continuum to the net line spectrum depends on the velocity gradient structure in the wind, thereby providing an indispensable diagnostic. Discerning the process depends primarily on resolving the He-like lines. In particular, the He-like resonance line must be separated from the He-like intercombination line [ΔE = 5 eV at 0.56 keV (O VII) and ΔE = 18 eV at 6.7 keV (Fe XXV)]. These requirements should be met easily by the proposed *Constellation-X* configuration. Note that meeting this resolution requirement (ΔE=5 eV) assures that for all the elements from oxygen to iron we will be able to resolve the important He-like forbidden line from the He-like intercombination line. *The detection of P Cygni profiles, produced by resonant line scattering and recombination accompanied by line-of-sight resonant absorption, requires higher resolution values (R~500). P Cygni profile analysis is critical to HMXB studies as the lines impose simultaneous constraints on the velocity field and the density field over the entire source volume.*

Figure 2



HMXBs show a rich abundance of fluorescent lines. The nature of the accreting flow, coupled with the action of the hard X-ray continuum, combine to highlight a unique aspect of the X-ray band: emission or absorption from every charge state can be observed in a single spectrum from a given source. For example, in GX 301-2, there is evidence of fluorescent lines from nine elements, including low-abundance elements such as manganese, cobalt, and chromium, in addition to more commonly observed elements (Sako et al. 2002). Additionally, resonant Auger destruction modifies Kα spectra from L-shell ions (Ross, Fabian, & Brandt 1996; Liedahl 2005). The net effect is that the line complexes have shapes that vary with column density, shapes that can be discerned with resolving powers of 500 or better.

Physics of Accreting White Dwarfs

Among the various classes of accreting compact binaries, cataclysmic variables (CVs) - semi-detached binaries composed of a low-mass secondary and an accreting white dwarf primary - are arguably the best laboratories in which to study accretion flows. Relative to neutron star binaries, white dwarf binaries have ~ 100 times lower velocities (v/c ~ 0.01). The relatively low velocities means that the lines are narrow ($\Delta E/E \sim 10^{-3}$), so that they stand out against the continuum and so provide detailed diagnostics of the plasma temperature, density, abundances, emission measure distribution, and velocity. Luckily, the space density of CVs is such that the closest systems are at ~ 100 pc, which almost makes up for the difference in intrinsic luminosities. (~1000 times lower luminosities; $L/L_{\rm Edd}\sim10^{-4}$). The relatively low luminosities means that photoionization is not as important in CVs, the relatively low temperatures means (blackbody temperatures T_{bb}~10 eV and virial temperatures Tvir~10 keV) that the plasmas in CVs produce X-ray spectra that are rich in emission lines with critical diagnostics at soft energies.

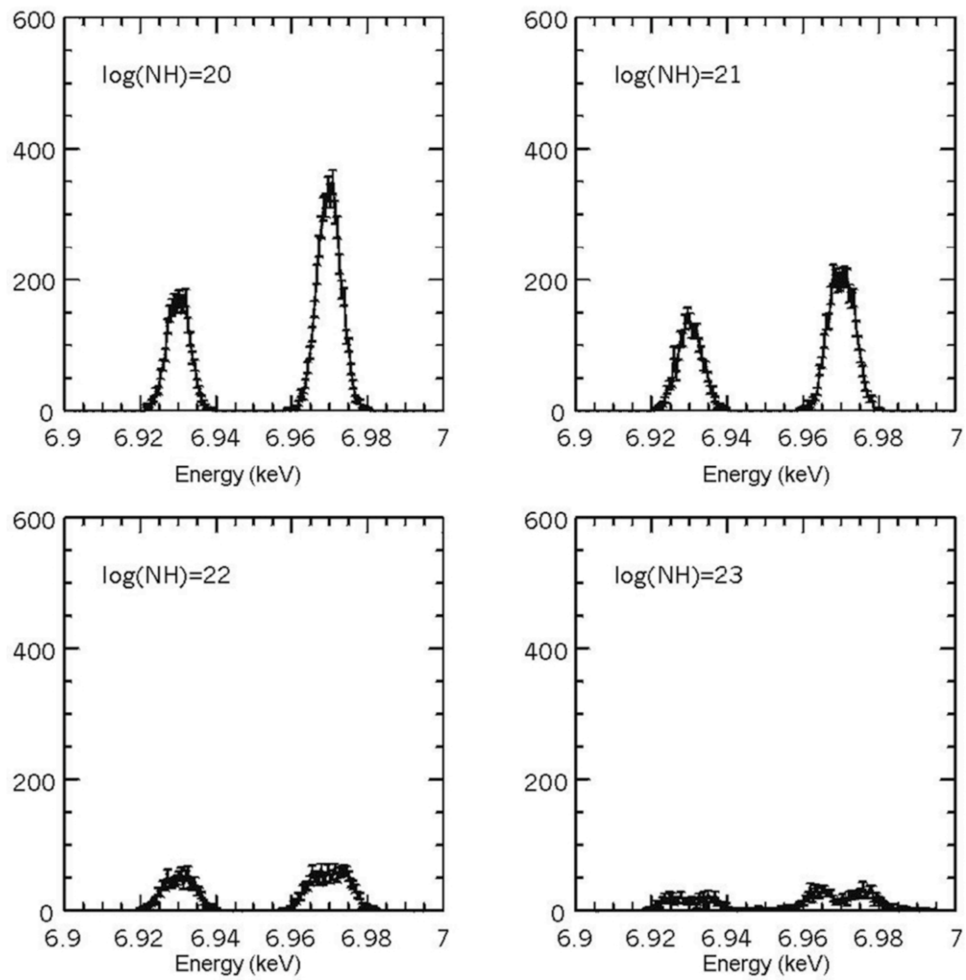
One of the great advantages of *Constellation-X* is that it will increase by a factor of ~ 100 the number of CVs for which we will be able to obtain detailed X-ray spectra. Among the numerous detailed studies possible with *Constellation-X*, we discuss three that are unique to CVs.

First, compared to stars, the X-ray emitting plasma in CVs is expected to be dense. In magnetic CVs, high densities are the result of the magnetic channeling of the accreting material onto small spots near the white dwarf magnetic poles, while in nonmagnetic CVs it is the result of accretion through a disk and boundary layer onto a narrow belt on the white dwarf surface. Mauche, Liedahl, and Fournier (2001, 2003) and Szkody et al. (2002) demonstrate the application of novel, high density Fe L density diagnostics to dense plasmas in EX Hya and U Gem. To apply these density diagnostics, it is necessary to resolve the Fe XVII 17.10 Å and 17.05 Å lines ($\Delta\lambda$ = 0.05 Å ; R ~ few times 350) and the Fe XXIII 11.74 A and the Fe XXII 11.77 Å lines ($\Delta\lambda$ = 0.03 Å ; R ~ few times 390). This is currently possible with the *Chandra* MEG ($\Delta\lambda$= 0.02 Å FWHM), but not with the *XMM-Newton* RGS ($\Delta\lambda$ ~ 0.07 Å FWHM). To apply the He-like R density diagnostic for high Z elements, it is necessary to resolve the intercombination and forbidden lines, which in S, Ar, and Fe are separated by 16, 19, and 31 eV.

A second area of CV science in which *Constellation-X* can make significant improvements is the study of systems in which the white dwarf is eclipsed by the secondary. Phase- and eclipse ingress/egress-resolved spectroscopy has the potential to constrain the geometric, as well as the thermal and density structure of the accretion flow. Currently, such studies are limited by counting statistics; the large effective area of *Constellation-X* will allow the first detailed studies of this kind.

Third, the unprecedented combination of energy resolution and sensitivity provided by *Constellation-X* will for the first time permit the study of subtle but extremely powerful line transfer effects that offer probes of the physical conditions in CV plasmas. One example involves recombination iron lines in settings in which opacity effects are important, for instance in the accretion column below the standoff shock above the surface of the white dwarf in magnetic CVs. Given the observed densities and the expected path lengths, the accretion column is expected to be optically thin to photoelectric absorption, thin-to-thick to Compton scattering, and thick to line scattering (Matt 1999, Terada et al. 2001). Figure 3 shows a simulated *Constellation-X* calorimeter observation of the line profiles of the Fe XXVI doublet for different column densities.

Figure 3



While for low column densities, the matter is optically thin in the line center and the line shape is a Voigt profile, but for larger column densities, the matter becomes optically thick in the line centers and the lines become double-horn shaped. This spectroscopic signature provides a probe of the geometrical and physical conditions of the emitting plasma.

Summary

The scientific goals outlined above all require a **spectral resolving power of order 1000 across the 0.5-8 keV band**. This spectral resolving power is of order that provided by the *Chandra* HETGS at energies below 1 keV; *Constellation-X*'s increased effective area with respect to *Chandra* HETGS automatically ensures that spectroscopy that can currently be successfully performed with this instrument will be possible on sources ~20 to 50 times weaker than characteristic bright Galactic binaries. To perform phase-resolved spectroscopy of emission from bursting neutron stars (spin frequencies up to ~700 Hz have been seen) requires the capability to **time resolve photon arrival times well below a millisecond** (eight phase bins in a 1/700 sec period results in a timing accuracy requirement of 1/5600 sec, or **0.16 msec**). During an X-ray burst, the X-ray flux increases dramatically, and the observatory must be able to handle high count rates without loss of spectroscopic or timing resolution (note that this does not require that no information be lost on any photon; counting slower at full resolution is of course acceptable, because to first order that just increases the observation time). The highest expected flux is ~ 1.0 ct/s/cm^2, which translates to count rates of ~7000 counts/sec in the microcalorimeter spectrometer, and ~650 counts/sec in the grating spectrometer.

We mention that it may be desirable to take advantage of *Constellation-X*'s large collecting area for the study of low spectral resolution, fast time variability. This will require the addition of a separate dedicated instrument (it is inconceivable that the current baseline spectroscopic instrumentation, or any reasonably extrapolated version of this instrumentation, will be able to successfully count at 10^7 counts/sec). If this is considered desirable, we recommend that a separate panel be convened to provide expert guidance, both with respect to astrophysical requirements as well as possible implementations.

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